The *Gaia* spectroscopic instrument (RVS): a technical challenge

ELSA conference 2010
Gaia: at the frontiers of astrometry

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Contents

Background: *Hipparcos* radial velocities

- The arguments for the measurement of radial velocities to accompany the Hipparcos astrometric data were originally made by Roger Griffin in a proposal in 1987 to the UK-SERC.
- The concept was to build 2 dedicated telescopes, of aperture ~1m, one in N hemisphere, other in S hemisphere and equipped with Coravel-type radial velocity spectrometers, to provide a full-scale survey of the 60000 stars in the *Hipparcos* input catalog (particularly those later than F5).

> rotations; still, it would obviously enhance the value of the Hipparcos transverse motions enormously if the radial velocities were available for the 60 or 70 thousand stars in the Input Catalogue with spectral types appropriate for measurement with radial-velocity spectrometers.
>
> Inasmuch as the SERC is now engaged on a 'forward-look' exercise, I have thought it appropriate to suggest that it should fund two small (1-m) automated telescopes which together would be capable of observing all the late-type Hipparcos stars once each every year, probably with a bit of power to spare. The prospective cost of little more than one million pounds sterling (plus very modest though unquantified running costs) seems amazingly inexpensive in relation to the power of the system, which would obviously revolutionize radial-velocity studies again.

Extract of letter from R Griffin to M Perryman, 2 July 1987

Background: *Hipparcos* radial velocities (ctd)

- Others agreed:

  Adrian Blaauw at 1988 Sitges Meeting on the Scientific Aspects of the Hipparcos Input Catalogue Preparation:

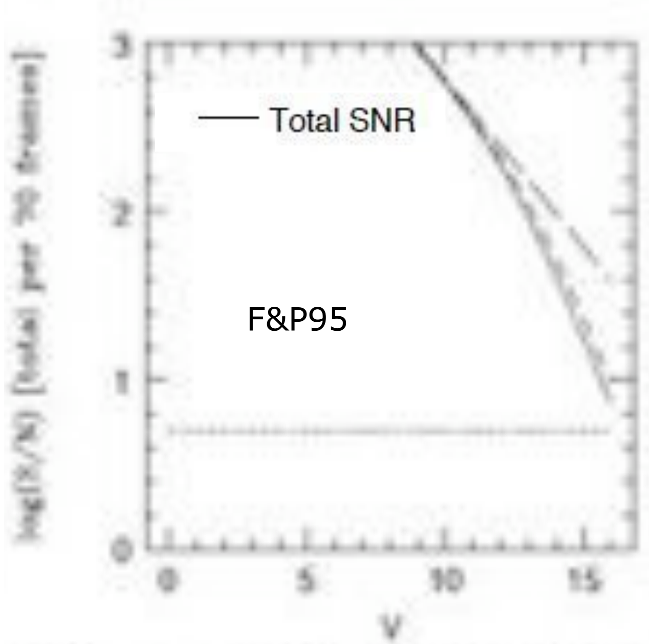
  '...there are, of course, things left one would like to see done. One of them, perhaps the most urgent, is in the field of radial velocities... ...there is no really dedicated Hipparcos radial velocity programme... May we be sure that, when the Hipparcos proper motions become available, we will not be faced with a deplorable lack of data on the third component of stellar motions?'

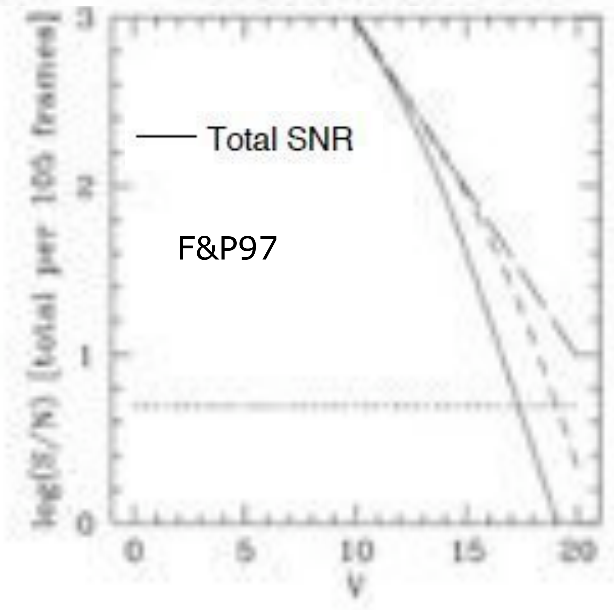
- Unfortunately SERC proposals were not successful (including resubmissions in 1990).

- Nordstrom et al (2004,7,8) publications for ~15% of *Hipparcos* Input Catalog

Early Ideas for *Gaia*

- In 1995 Favata & Perryman described slitless scanning spectrographs for both ground and space
- Identified main issues to be considered
- Concept updated in Favata & Perryman (1997) in the specific *Gaia* context (ARVI)
  - now space-based only
  - dedicated telescope system 0.9m diameter
  - wide field of view
  - narrower spectral range (around MgII)
  - importance of readout noise
- RVS instituted as part of reference payload for *Gaia*





Requirements for a *Gaia* Spectrograph

- Spectrometer allows science to be addressed in both
  - kinematics (radial velocity - 6th component of phase space, rotation)
  - astrophysical parameters (temperature, gravity, metallicity, α/Fe)
- Spectrograph needs to operate in scanning mode, for compatibility with the astrometry
  - slitless operation
  - higher background
  - exposure driven by scan rate set by astrometry
- Main parameters to trade off:
  - spectral resolving power
  - spectral range
  - radial velocity accuracy

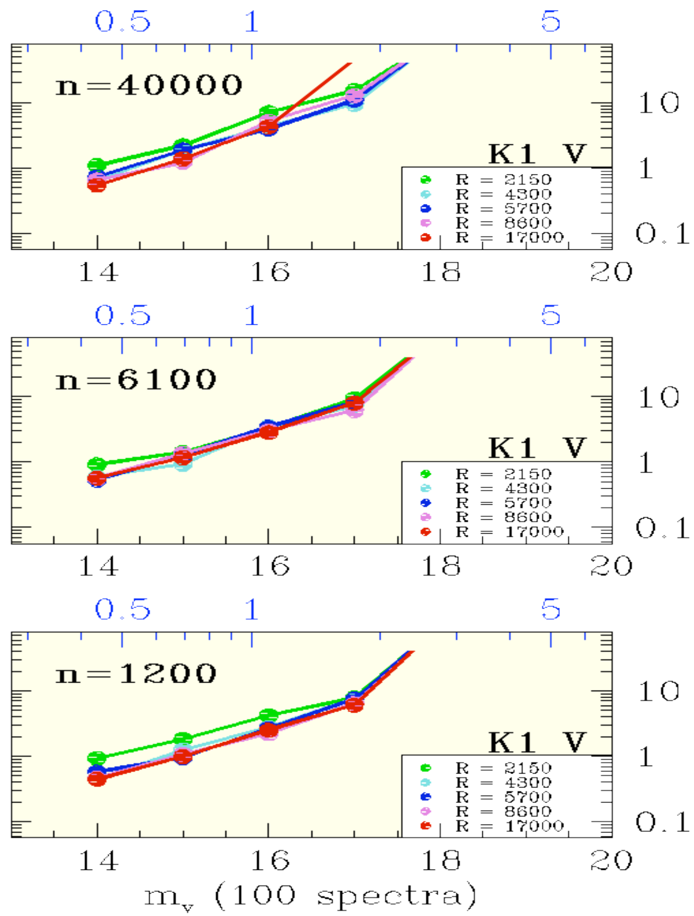
Further Technical Considerations

- End-of-mission radial velocity performance would be achieved by:
  - adding together in some way all of the spectra from different transits
  - combining all of the data in the spectrum to produce a single radial velocity by means of a cross-correlation

  ⇒ individual spectra could have *very* low countrates
- The astrophysical parameter determination (T_{eff} , *g*, *[Fe/H]*) requires
  - achievement of spectral resolving power
  - careful calibration
  - minimal effect by *Gaia* scan law

Spectral Resolving Power

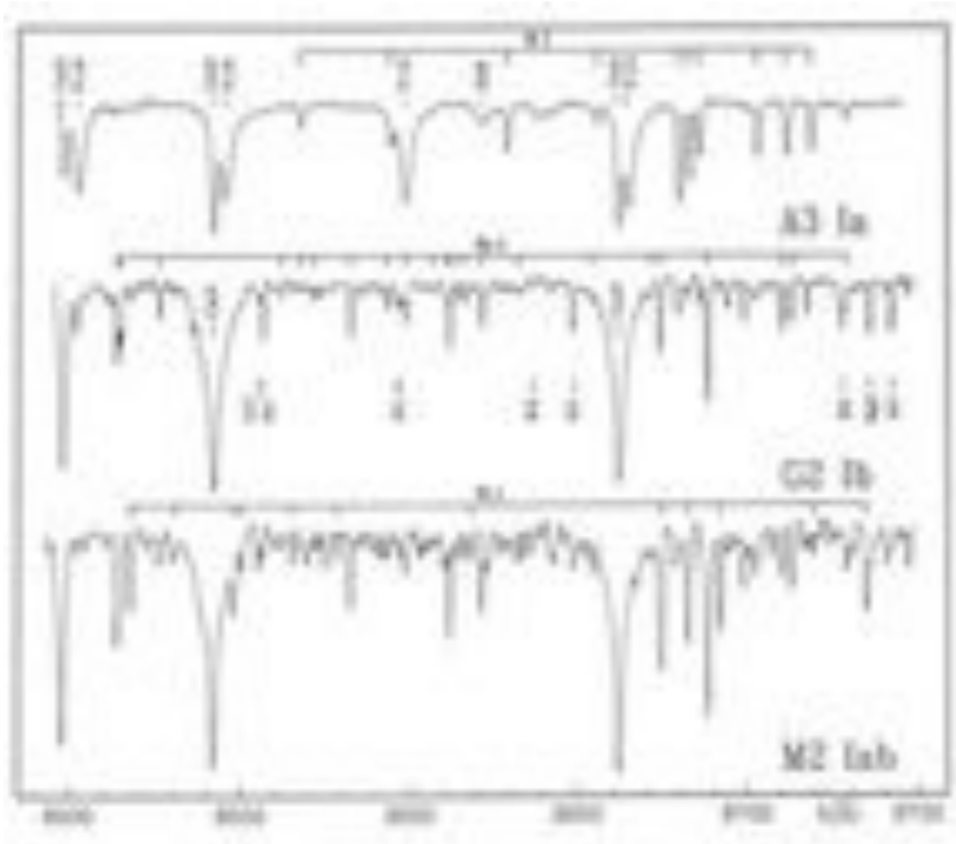
- Moderate resolving power required:
  - astrophysical parameters requires R>10000 (preferably R ~ 20000)
  - kinematics requires R>5000
- Higher resolving power
  - reduces signal per pixel
  - increases the length of the spectra
- Lower resolving power
  - provides insufficient spectral diagnostics
  - reduces line contrast
- Tradeoffs including crowding/overlaps indicated that R~10000 is optimal (eg Zwitter 2002)



Zwitter 2002

Spectral Range

- Initially the spectral range in the CTS Study had been around the MgII doublet at 500-550 nm
- In Nov 1998, Munari suggested that the wavelength interval be changed to the interval around the Ca triplet near 850 nm:
  - strongest lines in red/near IR
  - no contamination by interstellar contaminants
  - not affected by telluric absorption (in the atmosphere)
  - accompanied by many other line species (FeI, TiI, MgI, SiI)
  - Paschen lines in this region also (hotter stars)



Munari 1999

Radial Velocity accuracy & limiting magnitude

- Radial Velocity accuracy set by requiring them to be equivalent to the tangential accuracies from astrometry for giant tracers at large distances
- Limiting magnitude set by requirement to reach giant tracers

Thin Disk

- Typical tracer: gK
- Typical metallicity: $[Fe/H] \sim 0.0$
- Typical extinction: $A_v = 1 - 5$
- Required magnitude limit: $V = 17$ $(14 < m_v < 19)$
- b values: $b < 15°$
- Typical (one dimensional) velocity dispersion: $10 - 40 \mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 2.5 \mathrm{km\,s^{-1}}$ at $V \sim 16$ @ 10kpc ($l = 180°$)
- Required v_r accuracy: $\sim 2 - 3 \mathrm{km\,s^{-1}}$

Tracing Spiral Structure

- Typical tracer: Cepheids
- Typical metallicity: $[Fe/H] \gtrsim -0.5$
- Typical extinction: $A_v = 3 - 7$
- Required magnitude limit: $V = 17$ $(16 < m_v < 18)$
- b values: $b < 10°$
- Typical (one dimensional) velocity dispersion: $\sim 7 \mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 3.5 \mathrm{km\,s^{-1}}$ at $V \sim 16$ 10kpc
- Required v_r accuracy: $\sim 3 \mathrm{km\,s^{-1}}$

Thick Disk

- Typical tracer: Miras, gK
- Typical metallicity: $[Fe/H] \lesssim -0.5 \implies v_r$ accuracies shift by $\lesssim 0.5$ magnitudes.
- Typical extinction: $A_v \sim 2$
- Required magnitude limit: $V \sim 17$ $(15 < m_v < 19)$
- b values: $b < 30°$
- Typical (one dimensional) velocity dispersion: $30 - 50 \mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 11.5 \mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 8kpc ($l = 0°$) $\sim 18 \mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 20kpc ($l = 180°$)
- Required v_r accuracy: $10 - 20 \mathrm{km\,s^{-1}}$

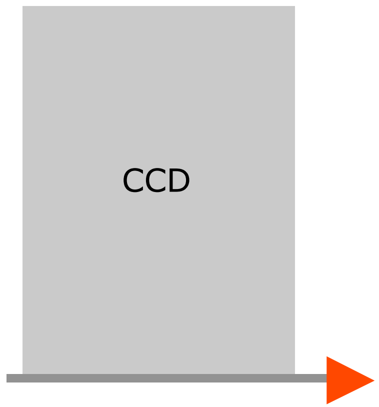
Wilkinson et al 2002

- Requirements driven by
  - thick disk and halo: $\sigma_{RV} \sim 15$ km/s for V=17
  - thin disk: $\sigma_{RV} \sim 3$ km/s for V=14

Next Trades: achieving S/N ratio

- Sufficient S/N ratio requires
  - enough signal
  - control of noise sources
- Enough signal can be obtained by
  - large telescope
  - large field of view
  - slow scanning rate
  - large number of detectors

  } ⇒ long exposures
- Noise is almost all CCD readout noise
  - minimised by reading out slowly
  - binning on-chip where possible
  - care paid to electronics performance
  - technology advances: L3CCDs



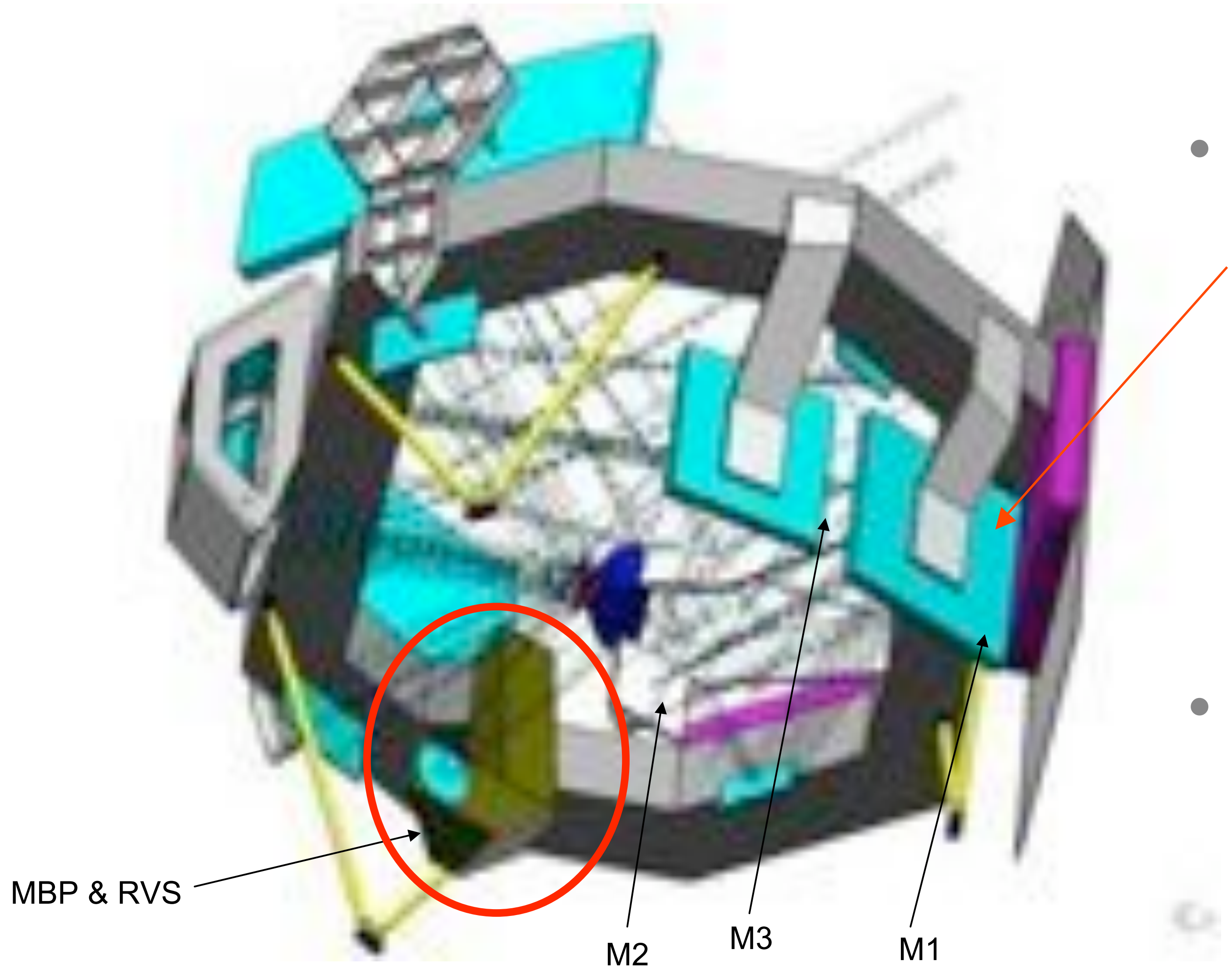
Next Trades: radiation damage

- A serious source of degradation would be radiation damage: damage to the Si lattice structure by MeV ions (mostly Solar flare)
- Regime of low signal levels in the presence of radiation damage was new:
  - ⇒ no guarantee that low signals would survive a large number of transfers from start of CCD to readout register
- Mitigating radiation effects by:
  - reducing the number of charge transfers
  - charge injection
  - diffuse optical background
  - shielding
- Charge injection and diffuse backround introduce too much noise (Poissonian+) which prevents their use
- Shielding ineffective for ions

Optimised RVS

- The optimised RVS therefore has:
  - R ~ 10000 even and constant over field of view
    ⇒ diffraction limited optics; low distortion optics;
    dispersion direction ∥ to scan direction
  - 847 - 874 nm bandpass; good rejection outside; low ripple inside
  - large field of view; slow readout speed; large optical feed
  - narrow detectors (radiation damage mitigation);
    low readout noise
- Such an instrument has been developed in the period 1997-present, in 3 conceptual phases: *Gaia*-1, *Gaia*-2, *Gaia*-3.

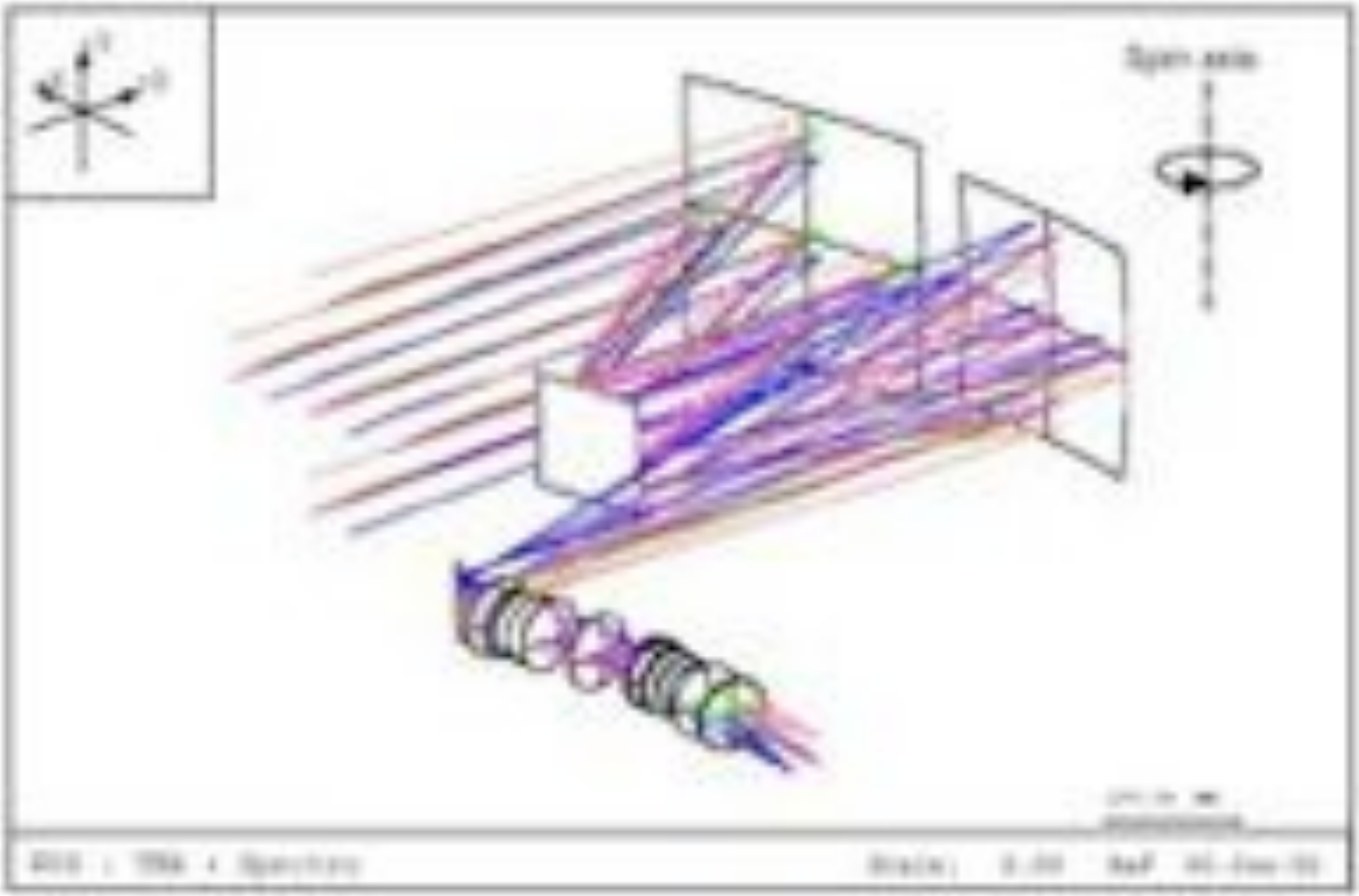
Gaia-1: Radial Velocity Spectrometer (Astrium)



- SLTRS study had separate Spectro telescope for RVS and Medium Band Photometer
  - smaller telescope
  - larger field of view
  - slower image scanning
- RVS optics were lens-based (dioptric)

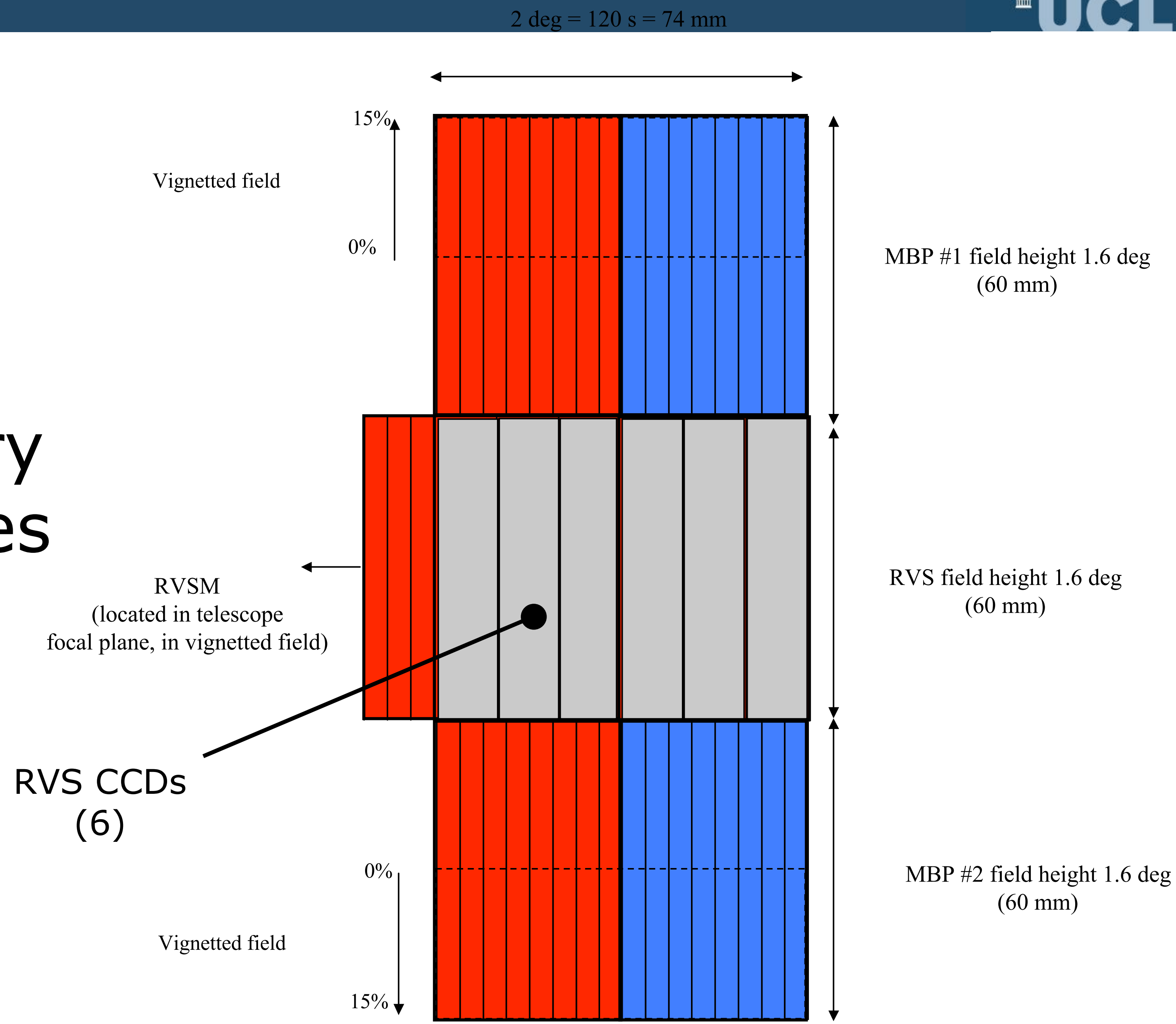
(from Astrium SLTRS Final Report EF/FR/PC/038.02)

Gaia-1: RVS optical path



(from SLTRS Final Report EF/FR/PC/038.02)

Gaia-1: RVS & medium band photometry focal planes

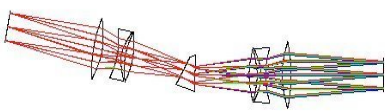
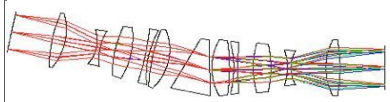
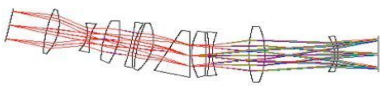
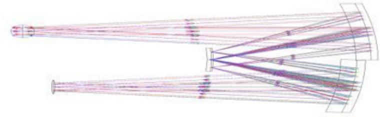


(from SLTRS Final Report EF/FR/PC/038.02)

Gaia arrangements, 2001-2005

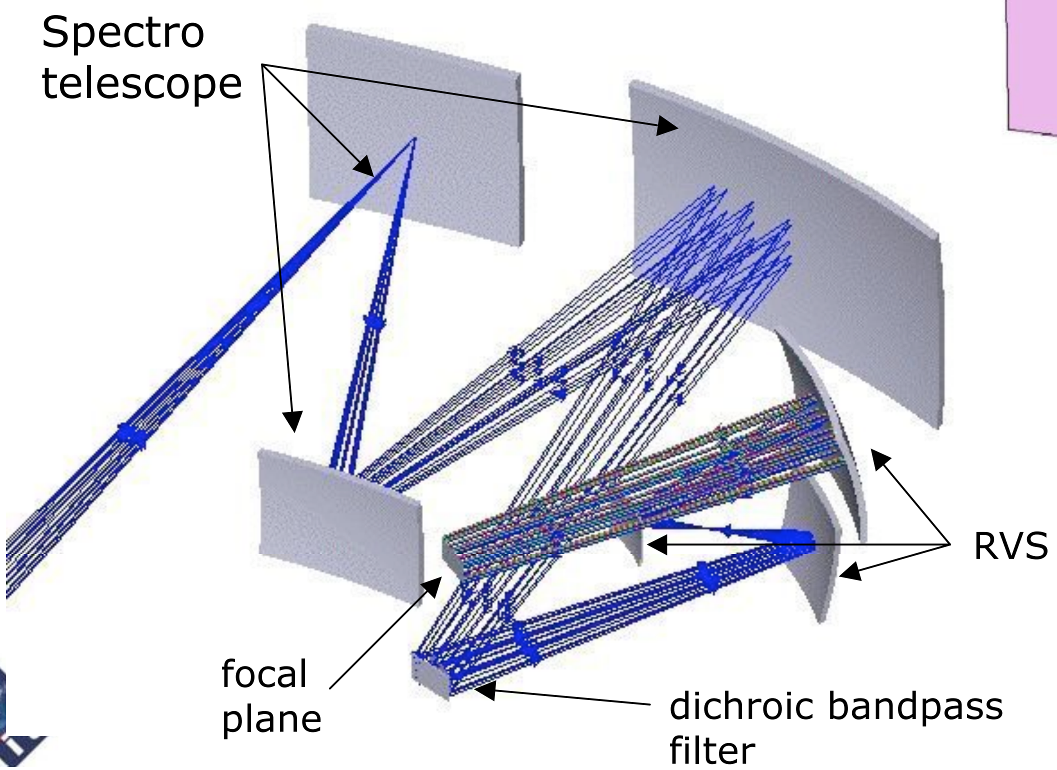
- Up until 1999, studies were carried out by Matra Marconi Space (now Astrium) for *Gaia* including the spectrometer reported in the GAIA CTS Study Final Report GAIA/MMS/TN/037.97
- From mid-2001, spectrometer development was taken forward largely by
  - the RVS Working Group (lead D. Katz, U. Munari) and
  - the RVS Consortium (lead M. Cropper) with institutes MSSL/UCL, GEPI ObsPM, Brunel U, Asiago, U Ljubljana
- Funding was from national agencies, and two ESA contracts
- Development took place in conjunction with both competing prime contractors (slightly separate designs)
  - Astrium Toulouse
  - Alcatel Space Cannes

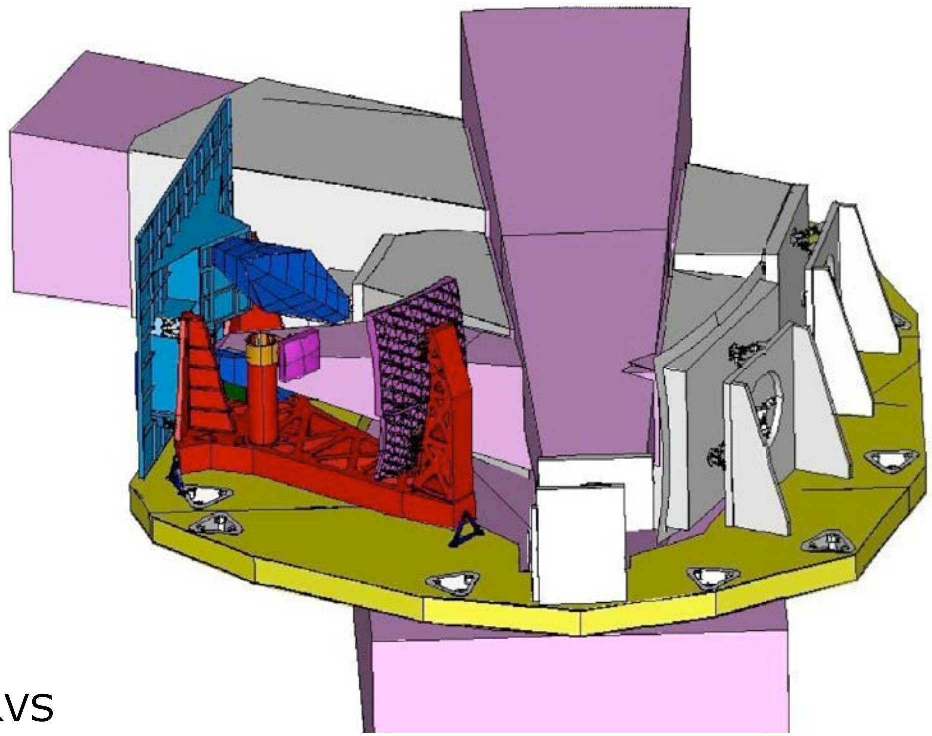
Gaia-2: improvements to optical design

	Triplet on both sides	Five lenses on both sides	Collimator : 5 lenses Camera : 4 lenses	Offner relay
Layout (unfolded view)				
Weight	18,5 kg	17 kg	17 kg	14,5 kg
Max track	1300 mm	923 mm	1000 mm	1400 mm
Dimensions x*y*z	750*570*200 mm^3 (folded)	800*600*250 mm^3 (folded)	215*215*923 mm^3	1400*800*500 mm^3
Total transmission	0,29	0,26	0,26	0,34
TDI PSF AL	5/10	6/10	3/10	7/10
TDI PSF AC	8/10	7/10	3/10	3/10
Spectral dispersion	10/10	10/10	10/10	10/10
Design flexibility	low	high	high	high
Probable sensitivity to tolerancing	high	high	low	low

Adoption of Offner Relay

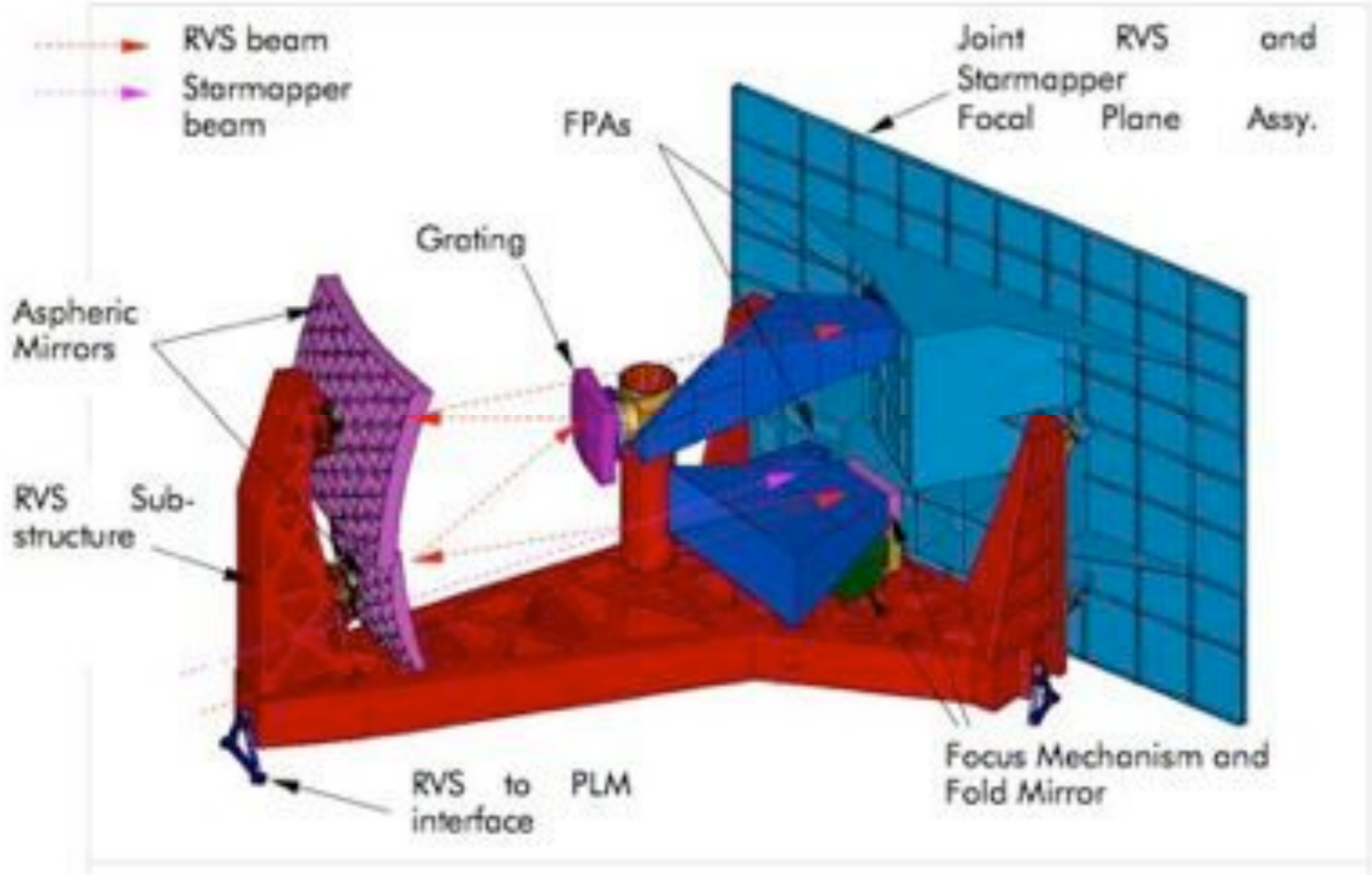
- Refinement of optical design led to development of Offner Relay spectrometer: elegant, high throughput, high optical quality
  - collimator mirror
  - spherical diffraction grating
  - camera mirror





RVS in Alcatel payload
(RVS Consortium)

Final RVS within Alcatel configuration

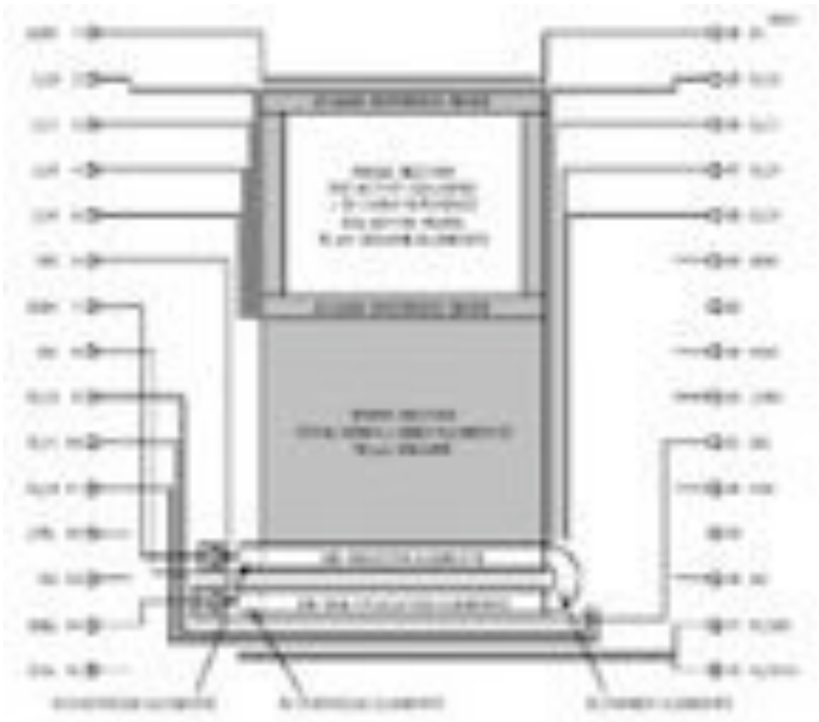


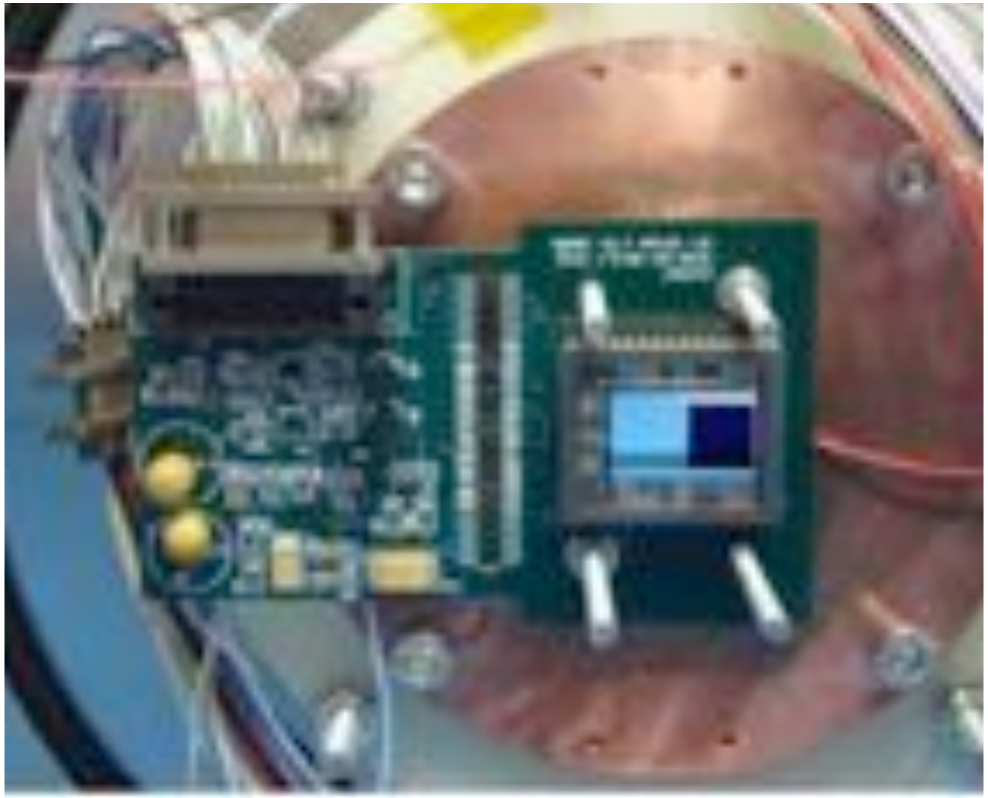
Focal Plane Array tradeoff

- A major tradeoff in the study was the decision whether to use
  - a small number of CCDs in the focal plane with a mechanism to compensate for the scan law across-scan motion, or
  - a larger number of narrower CCDs in the along scan direction, without a mechanism.
- A number of different options were considered, depending on
  - the number of CCDs in the across-scan direction,
  - whether L3CCDs or conventional CCDs were to be used,
  - whether a mechanism was to be incorporated and
  - whether there would be on-board processing (pre–processing) to combine the data from different CCDs.
- The outcome of this tradeoff was that configurations with more narrow CCDs of the L3CCD type were preferred

RVS Focal Plane - L3CCDs

- New technology developed for RVS focal plane using L3CCDs which have amplification on-chip to minimise readout noise (essentially 0) with deep depletion (high resistivity) Si for good red response.





L3CCD97 devices undergoing lifetesting at Brunel

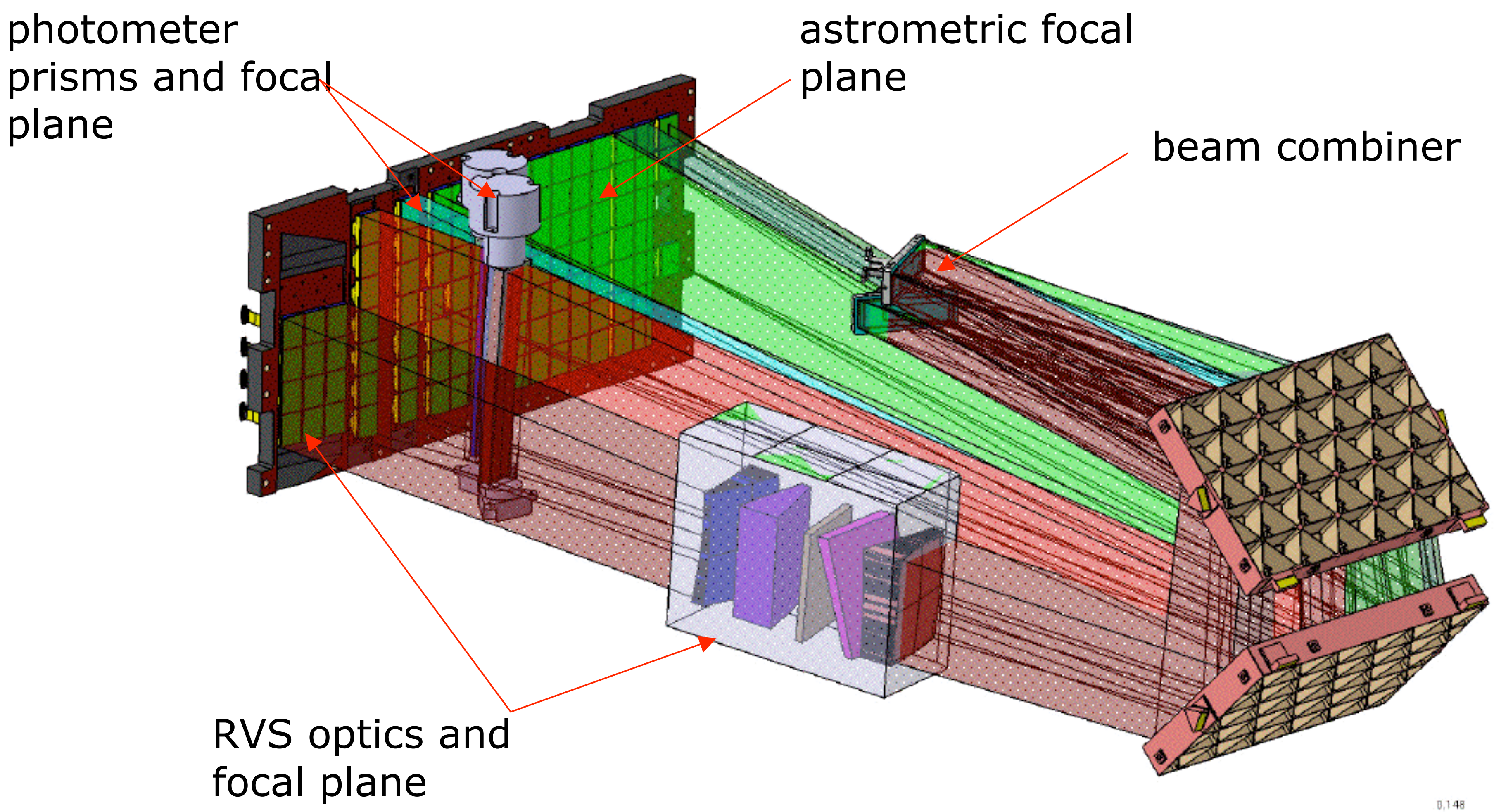
Gaia-2: Telemetry issues

- On-board combination of data was required to fit within the telemetry allocation for RVS

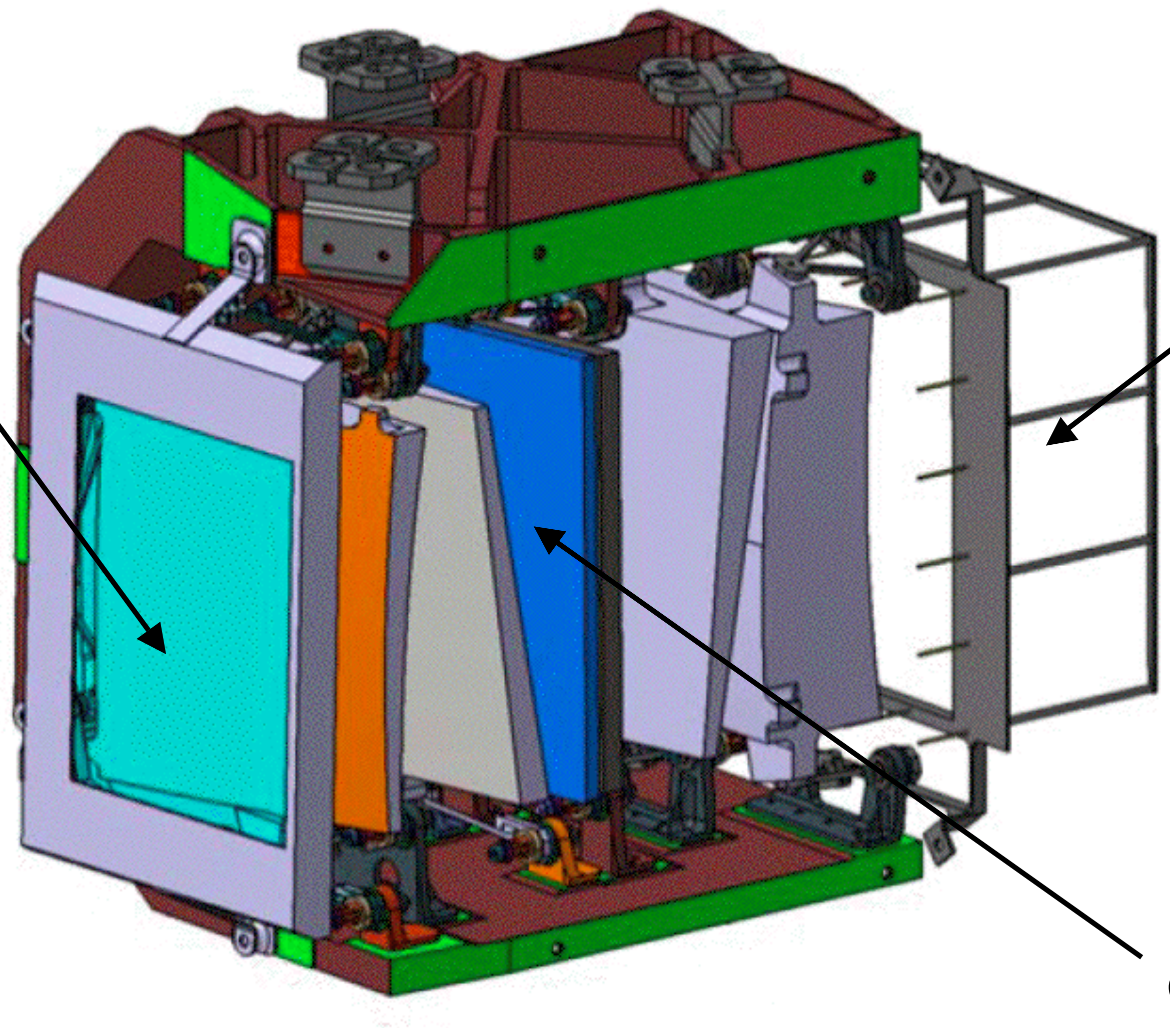
Gaia-3: in 2005/6, a new configuration…

- Astrium proposed a different concept for the *Gaia*-3 design
  - RVS uses Astro telescopes
  - spectral windowing and binning (+collapse to 1-D) rather than entire focal plane; no on-board processing
  - conventional CCDs (red sensitive)
- Advantages (from RVS perspective)
  - less crowding of images
  - no on-board processing required
- Disadvantages (from RVS perspective)
  - 2 spectral resolutions (HR/LR) required to minimise readout noise
  - generally only 1-D data; difficulties in dealing with overlaps and high density regions
  - short exposures and non-L3CCDs lead to reduced performance (~1 mag)
  - radiation damage significantly worse because of wide CCDs
  - fewer transits recorded
  - stability of readout speed lost (⇒ PEM-CCD bias instability)

Gaia-3 configuration

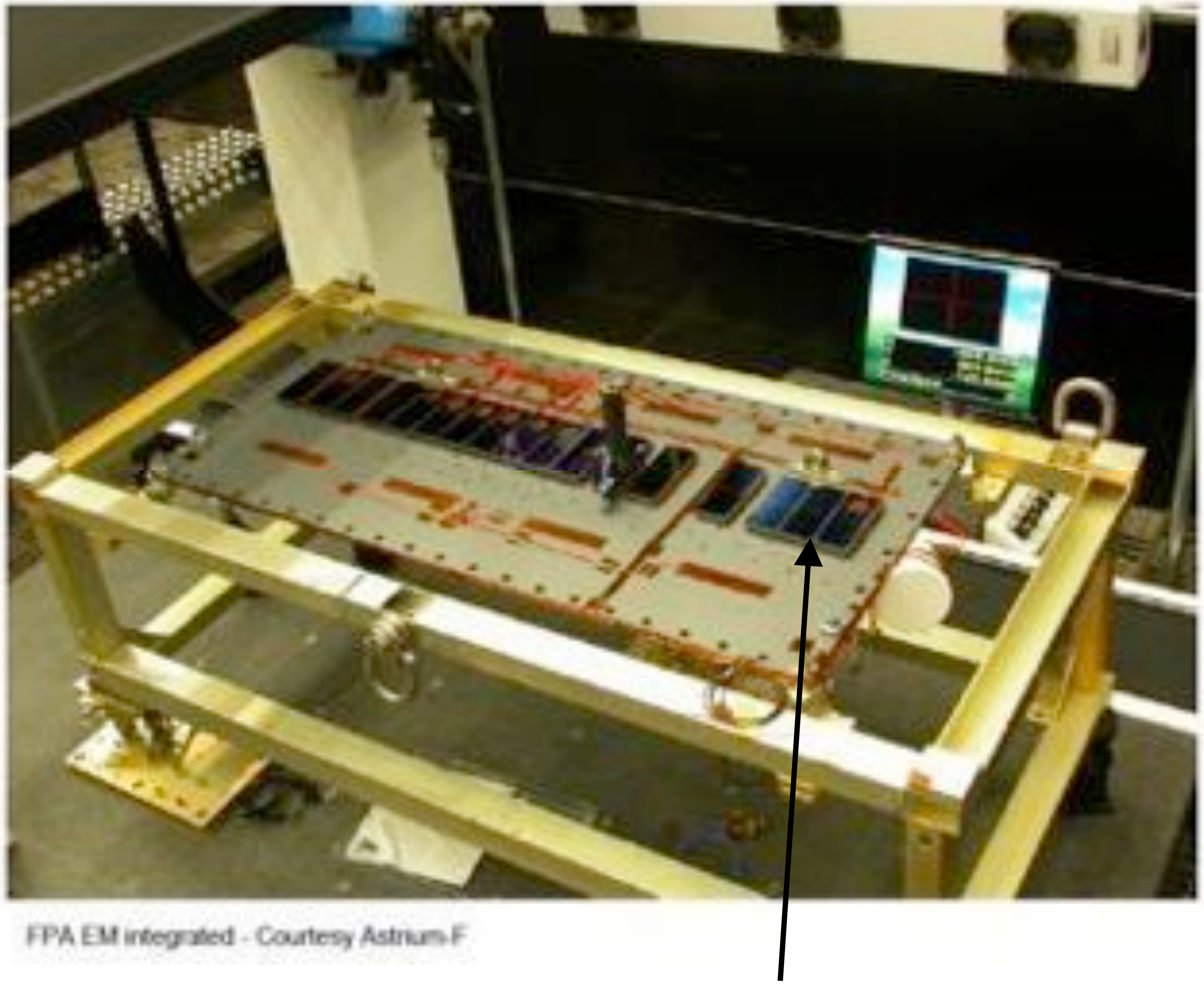


RVS Opto-mechanical Assembly at CDR



credit: Astrium

Focal Plane Structure - Engineering Model (EM)



FPA EM integrated - Courtesy Astrium-F

FPA EM

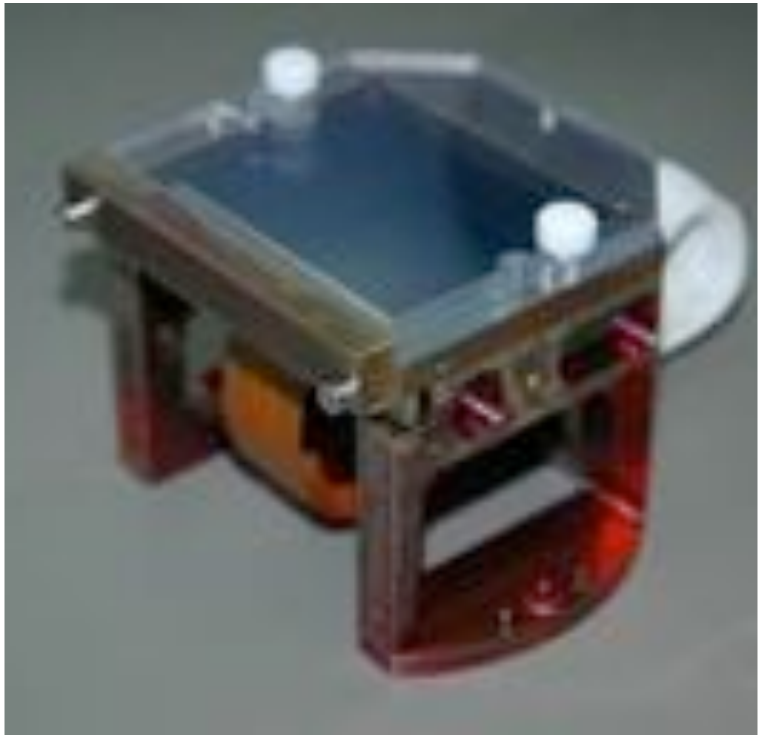
1 Complete row of CCDs.
1 Partially populated row of CCDs.
26 Proximity Electronics Modules.
2 Interconnection Modules.
1 Wave-Front Sensor OMA.

Tests objectives:

Electrical & Functional testing.
Characterisation of the Electro-Optical performances (i.e. validation of the performances in flight representative configuration).
Thermal balance.
EMC (conducted emission / susceptibility).

Red CCDs and Proximity Electronics Modules

flight CCD



credit: e2v

PEM

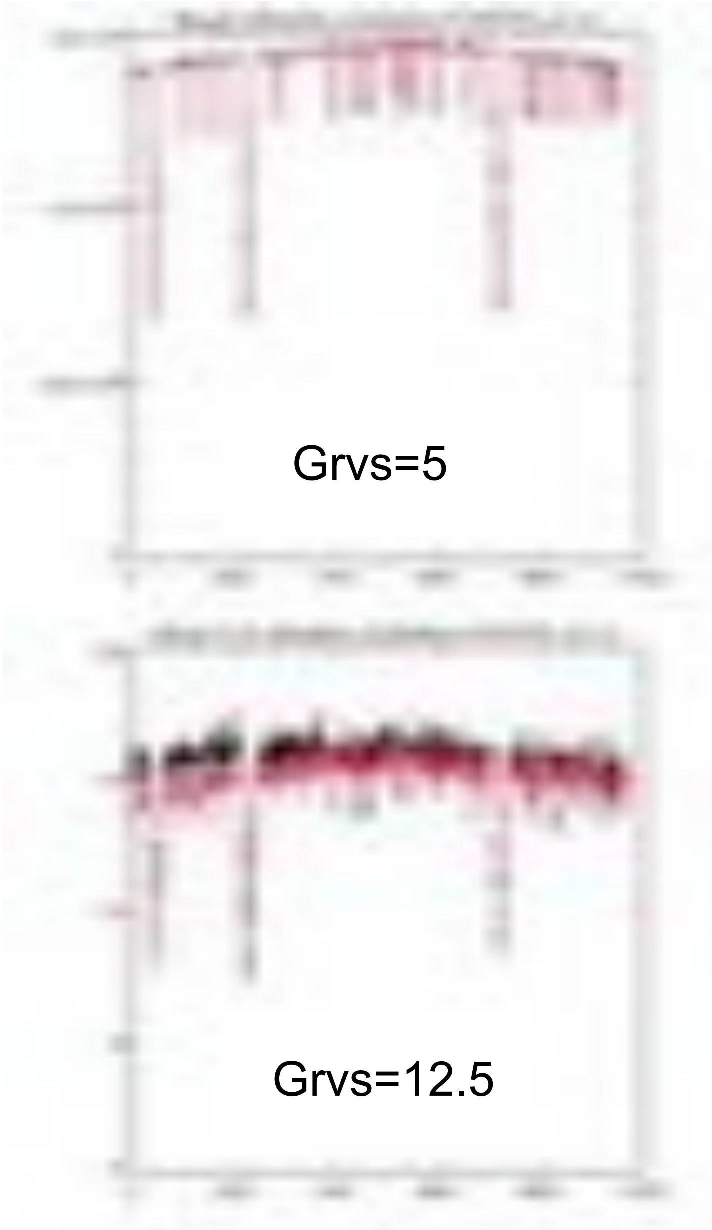
credit:CRISSA

RVS: Implementation Difficulties

- RVS hardware implementation is progressing well (PLM CDR)
- 3 main difficulties have arisen
  - radiation damage issues
  - PEM-CCD bias non-uniformity
  - serial register charge transfer inefficiency (CTI)
- New technical challenges…
- Each addressed by combination of calibration and software measures (and some hardare improvements)

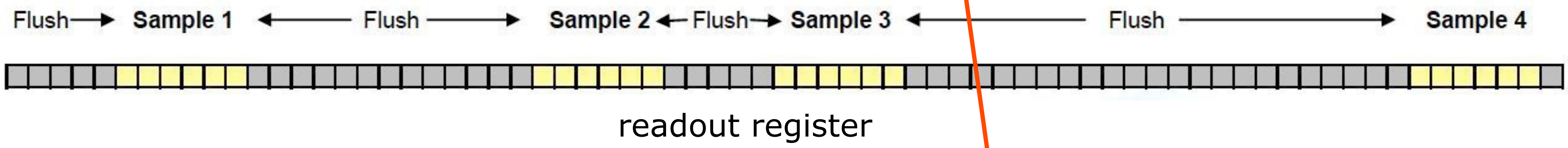
Radiation effects in RVS

- Leading edge of spectrum is consumed by traps in radiation-damaged Si within pixels
- Leads to
  - magnitude-dependent radial velocity bias
  - changes to line equivalent width
  - reduced S/N ratio from charge loss
- However: even very low signals (1 e^-) are recovered after 4500 line shifts in the CCD
- Recovered by modelling with radiation damage models (eg CDM02) and post-calibration

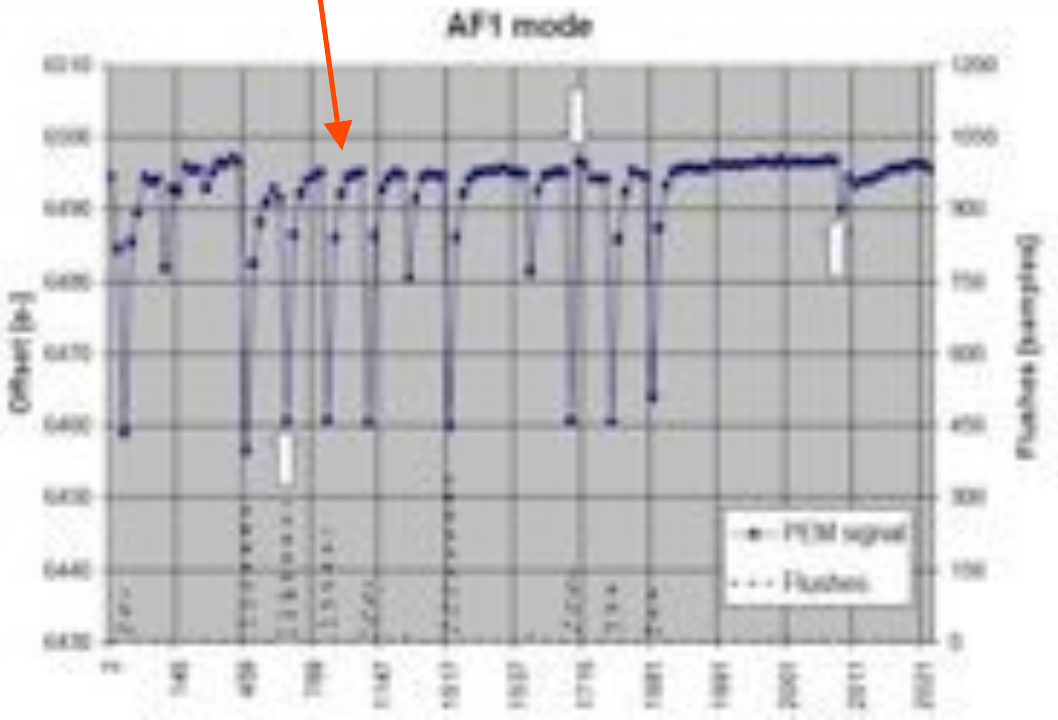


PEM-CCD bias anomaly: black-level shifts

- PEM shows small changes in bias level following a rapid readout dump between pixels containing star spectra

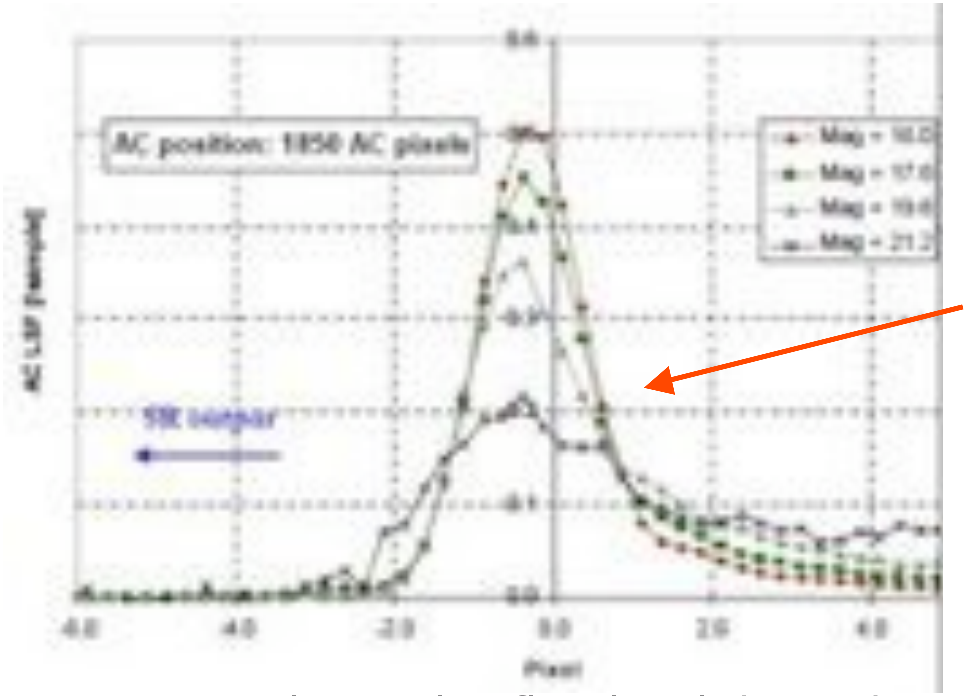


- Problem also occurs during line transfers
- Major impact is intermediate brightness stars
- If duration of flushes is known can be calibrated adequately
- Final corrections in data processing

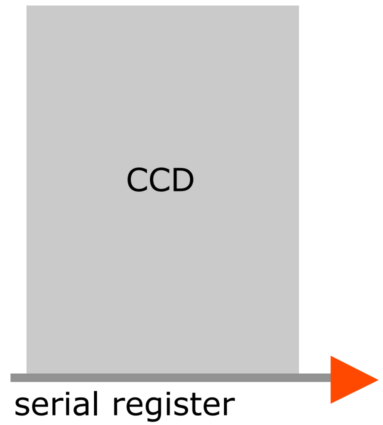


Serial register charge transfer

- Charge transfer in serial register is not as good as anticipated, because of rapid clocking during flushes (~5 MHz) even in absence of radiation damage



flux-level dependent



- Loss in trailing tail is flux-level dependent
- Will at some level impact RVS when linked with the PEM-CCD bias anomaly and radiation
- Effect being quantified using test results from Astrium

Summary

- RVS came about in order to complete the *Gaia* suite of instruments to measure kinematic and astrophysical properties of stars in the MW
- Photon-starved nature of the instrument (low exposure levels) has given rise to many unique challenges - unusual parameter space
- Many different configurations and technologies have been examined, tested and built to address the science requirements
  - inspirational, perspirational process
  - subject to many considerations: technical, programmatic, sociological
- Inputs from science groups, industry, ESA: massive effort
- Some capabilities were lost in the transition from *Gaia*-2 to *Gaia*-3
- BUT: in the end we have a *Gaia*-RVS that will broadly do what we set down for it to do…
- *Gaia*-RVS data: a massive resource of $\sim 10^8$ multi-epoch spectra